Fundamental Suppression of Entanglement-Induced Gravity: Constraints on Detectability and Theoretical Viability

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Abstract

We establish rigorous upper bounds on quantum entanglement contributions to gravitational interactions using established principles of quantum field theory and general relativity. The ratio of entanglement-mediated stress-energy to conventional matter density is bounded by $|T_{\mu\nu}^{\text{ent}}|/|T_{\mu\nu}^{\text{matter}}| \leq (\ell_{\text{P}}/L)^2$, where L is the system size. For laboratory systems, this yields suppression factors $\leq 10^{-68}$, rendering entanglement–gravity coupling fundamentally undetectable in any conceivable Earth-based experiment. These results place severe constraints on emergent gravity theories and provide guidance on where experimental resources should not be allocated.

1 Introduction

The relationship between quantum entanglement and gravity remains an active area of theoretical speculation. Various proposals suggest measurable entanglement–gravity coupling effects. In this work, we demonstrate fundamental upper bounds on such coupling using only established results from quantum field theory in curved spacetime [3, 4] and general relativity. The suppression derived is exponential in macroscopic settings, effectively closing off entire classes of laboratory experiments.

2 Scaling Arguments and Fundamental Bounds

2.1 Entanglement Stress-Energy

For a quantum system in curved spacetime, the stress-energy tensor receives contributions from quantum correlations. We isolate the entanglement contribution as:

$$T_{\mu\nu}^{\text{ent}} = \langle\psi|T_{\mu\nu}|\psi\rangle_{\text{ren}} - \text{tr}(\rho_A T_{\mu\nu})_{\text{ren}}, \tag{1}$$

where ρ_A is the reduced density matrix, and renormalization is performed appropriately for curved spacetime [3].

2.2 Holographic and Dimensional Bounds

The entanglement entropy is bounded by the covariant entropy bound [2]:

$$S_{\text{ent}} \leq \frac{A}{4\ell_{\text{P}}^2}, \tag{2}$$

where A is the boundary area of the region and $\ell_{\text{P}} = \sqrt{\hbar G/c^3}$ is the Planck length.

Dimensional analysis combined with this bound yields:

$$|T_{\mu\nu}^{\text{ent}}| \lesssim \frac{\hbar c}{G} \cdot \frac{1}{L^2} \cdot \left(\frac{E}{E_P}\right)^2, \tag{3}$$

where E is the energy scale and $E_P = \sqrt{\hbar c^5/G}$ is the Planck energy.

2.3 Fundamental Suppression

The key result follows:

$$\frac{|T_{\mu\nu}^{\text{ent}}|}{|T_{\mu\nu}^{\text{matter}}|} \lesssim \left(\frac{\ell_{\text{P}}}{L}\right)^2. \tag{4}$$

For any macroscopic system, this ratio is exponentially suppressed.

3 Experimental Implications

3.1 Laboratory Sensitivity Limits

Typical suppression values:

- $L = 1$ m: $\sim 10^{-68}$
- $L = 1$ mm: $\sim 10^{-62}$
- $L = 1$ μm: $\sim 10^{-56}$

Torsion balance experiments reach $\sim 10^{-14}$ relative precision [5], falling short by over 50 orders of magnitude.

3.2 Revising the LIGO Estimate

While LIGO's strain sensitivity reaches 10^{-23}, constraints on exotic stress-energy sources remain far above the suppression bounds derived here. These experiments are therefore not approaching detectability.

3.3 Impossibility Theorem

Theorem: No Earth-based experiment can detect entanglement–gravity coupling.

Sketch of Proof: Minimum detectable signals scale as $(\ell_P/L)^2$; experimental precision plateaus at $\sim 10^{-15}$. With $\ell_P/L_{\text{lab}} \sim 10^{-34}$, the gap is unbridgeable.

4 Cosmological and Astrophysical Regimes

4.1 Potential Detection Scenarios

1. $L \sim \ell_P$: Planck-scale systems
2. $L \sim R_H$: Early universe/Hubble scale
3. $L \sim r_s$: Near black hole horizons

4.2 CMB Constraints

From $\delta\rho/\rho < 10^{-5}$, we obtain:

$$\frac{|T^{\text{ent}}_{\mu\nu}|}{|T^{\text{matter}}_{\mu\nu}|} < 10^{-5}. \tag{5}$$

This restricts entanglement gravity effects at redshift $z \sim 1100$.

5 Theoretical Implications

5.1 Constraints on Emergent Gravity

Verlinde-style models must satisfy:

$$L_{\text{emergence}} > \sqrt{10^{14}} \cdot \ell_P \sim 1 \text{ mm} \tag{6}$$

to avoid laboratory falsification [5].

5.2 Quantum Gravity Falsifiability

Theories predicting:

$$\frac{|T^{\text{ent}}_{\mu\nu}|}{|T^{\text{matter}}_{\mu\nu}|} > 10^{-14} \tag{7}$$

are ruled out unless they fine-tune or invoke large emergent length scales.

5.3 Speculative Corrections from Fisher Information

We speculate that quantum distinguishability (Fisher information) may play a role in renormalizing effective masses or stress-energy, leading to potential EP deviations. This remains speculative and unconfirmed [6, 7, 8].

6 Conclusion

We conclude:

- Entanglement–gravity effects are **undetectable** in laboratory settings.
- Emergent gravity theories must operate above mm-scale.
- Cosmological and horizon-scale observations are the only viable probes.
- Fisher information-based corrections remain theoretical.

References

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